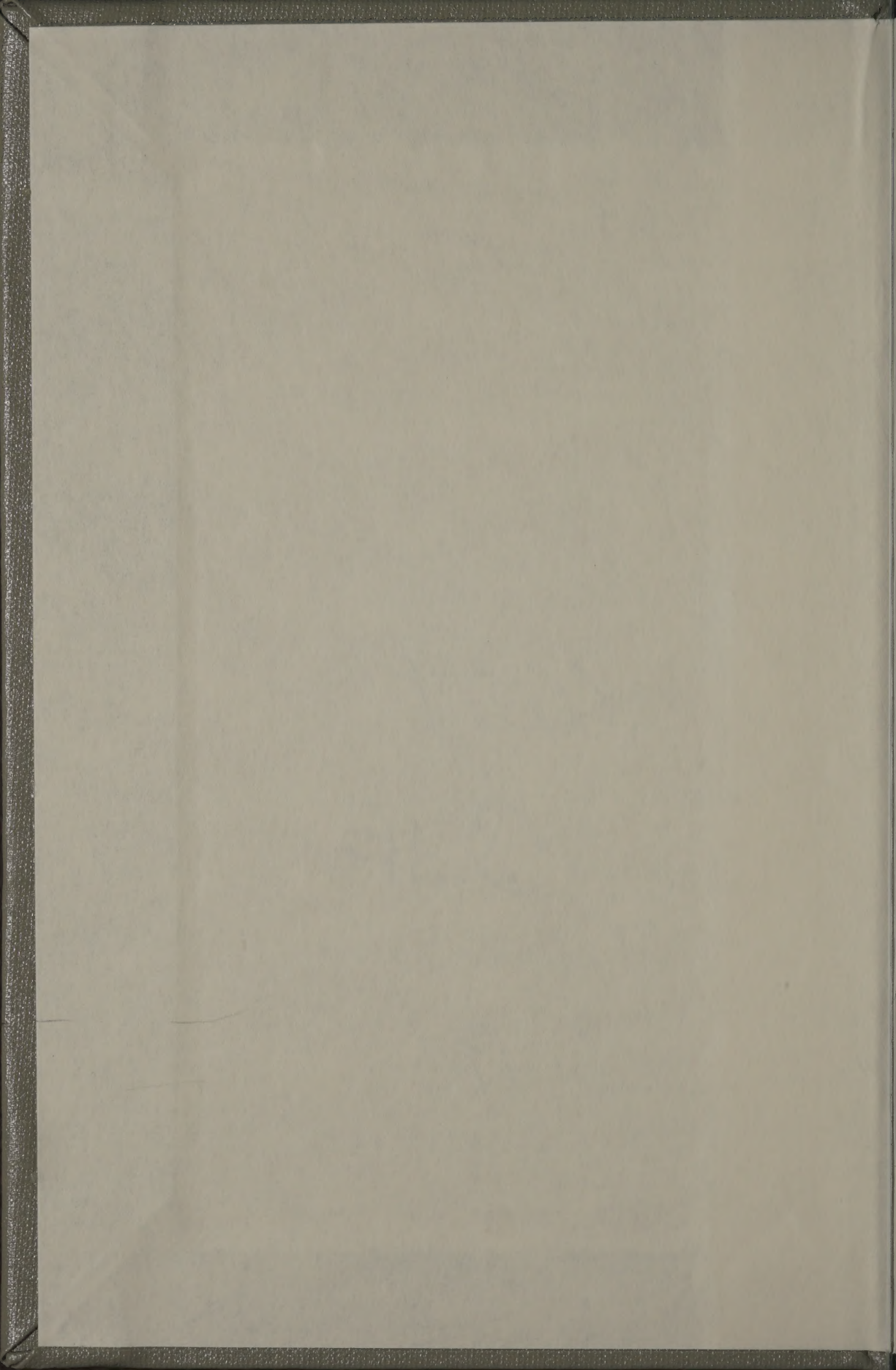
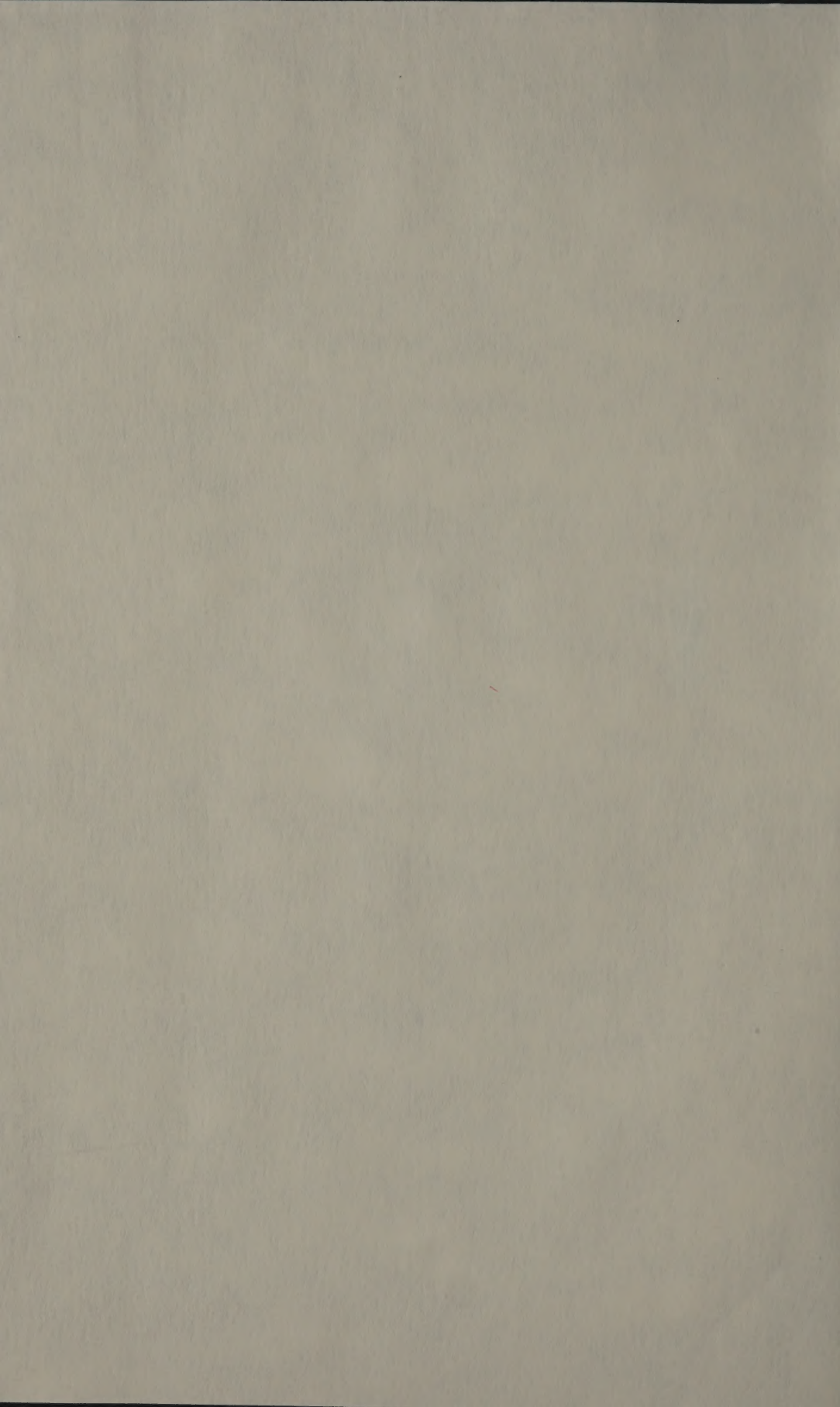


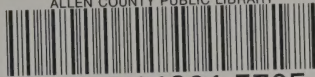


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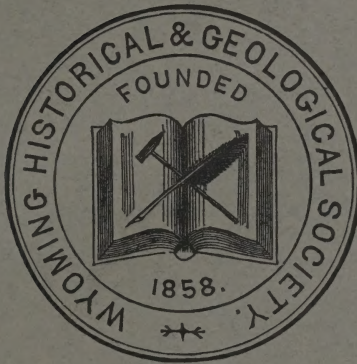
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THE ORIGIN AND CONSTITUTION OF COAL

BY

REINHARDT THIESSEN

(Research Chemist, U. S. Bureau of Mines,
Pittsburgh Experiment Station)



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THE ORIGIN AND CONSTITUTION OF COAL.*

By REINHARDT THIESSEN†

READ BEFORE THE WYOMING HISTORICAL AND GEOLOGICAL SOCIETY,
WILKES-BARRÉ, PA., MARCH 14, 1924.

INTRODUCTION.

Of all our natural resources, coal has had the greatest influence on economic conditions, on the advancement of industry, and on the general welfare of the nation; it has been the chief factor in the industrial revolution, yet it has received the least study and attention. What we know about the chemistry of coal is almost negligible. It is true that chemists have considerable knowledge of the products of distillation, but probably none of those substances are to be found in coal as such.

Coal has been called "petrified sunlight", because the daylight of millions of years ago is wrapped up in the black gloomy masses brought to daylight by miners. According to calculations of geologists, millions of years ago (eons before man appeared; epochs before the giant dinosaurs wallowed in the mud of the western plains; during a period called the Carboniferous), conditions were favorable for the development of numerous and extensive swamps. These swamps were the sources of the coal beds of to-day. Through study and comparisons we know now that these beds were formed in swamps in a manner similar to the formation of the peat beds of to-day. From a study of the peat beds we may learn very much of the origin, composition, and general nature of coal.

THE PEAT BOG OF TO-DAY.

Peat is formed in rather shallow, undrained basins or depressions, or plains, under conditions that were favorable to luxuriant plant growth but unfavorable to complete decay, with the result that semi-decayed plants accumulated. Such

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accumulation takes place in swamps, bogs, or sloughs. The most common type is the wooded swamp, usually designated according to the predominant trees growing therein. Many of such swamps are found in Minnesota, Wisconsin (Plate I, A and B), and Michigan, and the Dismal Swamp of Virginia and North Carolina is an example of an unusually large one. These swamps in many respects are much like the coal swamps of the Carboniferous period. The original vegetation of the wooded swamp mentioned consisted of a dense luxuriant growth of moisture-loving trees, such as the white cedar, tamarack, spruce, balsam, bald cypress, black ash, and a few others, only a few species growing together in a given swamp. Shrubbery is absent, a thick carpet of mosses and lichens is growing on the hummocks and prostrate trunks underneath the trees, but very few herbs of any kind are found. Most of the tree trunks are covered, particularly on the north side, to a considerable distance upward with a coat of mosses and lichens.

A swamp of this kind in its native condition is awe-inspiring, and puts one in a peculiar frame of mind. The sunshine trickles through the branches but sparingly; a twilight condition prevails even at high noon; almost semi-darkness prevails on cloudy days. A breeze is only manifested by a sigh in the tree tops, a gale by a howl and a moan and the cracking of tree-trunks and branches rubbing together. On calm days the silence is distressing. The beauty of the surroundings, no matter what time of the year, is one of grandeur. In some places most of the trees stand straight as a plumb-line (plate I A), in others the wildest entanglement of broken down or reclining trees with their branches exists (Plate I B).

The ground under these conditions is very wet, submerged for the most part in wet seasons, and thoroughly soaked with water even during the driest periods (Plate II). Walking is difficult, and advance can generally only be made by jumping from hummock to hummock. A jump short of the mark



PLATE I. A.—In a peat bog of Wisconsin during a dry season. Note the partly buried tree trunks. During most of the year all but the hummocks is under water. The trees are white cedars with a few tamarack and black ash. A normal appearance.

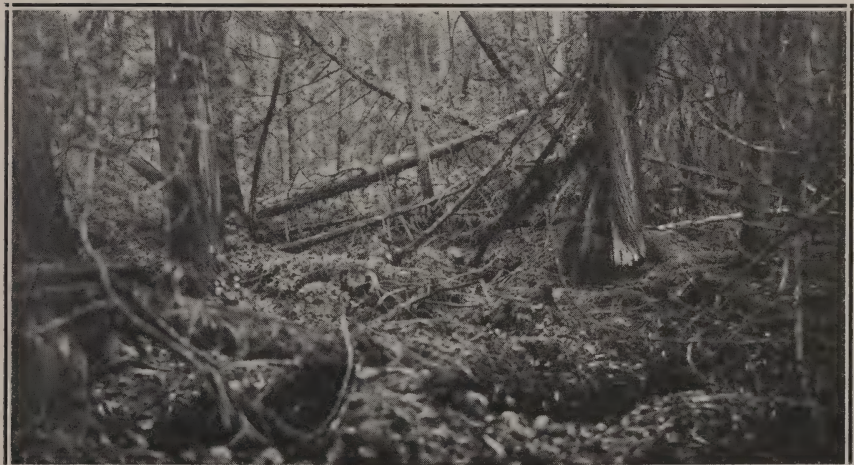


PLATE I. B.—In a peat bog of Wisconsin, during a dry season, in which the fallen and reclining and low branches make passage almost impossible. The ground consists mostly of tree trunks covered up with débris.

will find the visitor deep in a pool of water or mire. The swamp is further impeded by a wild entanglement of reclining and fallen trees and their branches (Plate I B). As already indicated, every spot not under water is covered with a mat of mosses and lichens. A litter of small twigs, leaves, and general débris is dominant everywhere. Particularly noticeable are the leaves or needles of the conifers that usually compose the flora (Plate II B).

The surface layer, or sub-stratum itself, consists of the components named above in all conceivable stages of decay, fragmentation, and maceration, penetrated with a thick network of the roots and rootlets of the trees growing in the swamp. These roots lie relatively close to the surface in a horizontal position. They penetrate but a few inches.

The real peat lies beneath the surface layer. Its depth varies from a few feet to 30 feet or more; 10 feet is a common depth. This mass consists of the components already enumerated, but everything is in semi-rotten condition. The tree trunks, limbs, branches and parts of them are found in abundance; but they can easily be cut with a spade, and molded like clay. The spaces between the logs, branches, twigs, and roots, and fragments of these are filled in with a fine black mud. When this mud is examined with the microscope it is shown to consist not of earthy matter but of the degradation matter of anything and everything once living in the bog—namely, of wood, bark, leaves, mosses, lichens, spores, pollen grains, and resinous matters.

The mass as a whole behaves and appears more like a mud than anything else, and contains from 80 to 90 per cent. of water. When it is dried, which is accomplished with some difficulty, it is hard and brittle, and forms a good fuel.

COMPOSITION OF PLANTS.

Since coal was formed from plants it is quite important to consider their chemical composition.



PLATE II. A.—In a peat bog of Wisconsin at close range. A large part of the ground is under water.



PLATE II. B.—In a Wisconsin peat bog at close range, showing the nature of the litter on the ground. The foreground is under water.

Green plants manufacture their own foods from water, drawn up by the roots; and carbon dioxide, taken in by the leaves, by means of the sunlight through the aid of chlorophyll, the green coloring matter of the leaves. This process is called photosynthesis. The first product is formaldehyde. This is condensed to glucose, from which in turn cane-sugar, starches, and cellulose are formed. From the sugars and starches, with the addition in some cases of nitrogen and sulphur, all other plant substances are then formed by the plant, either during a building up or assimilation process or a tearing down or disassimilation process. Green plants are therefore, to speak figuratively, absorbers of sunlight, or better, of solar energy. For that reason particularly coal has been called "petrified sunlight", and "born of the sun".

The products thus formed by plants, and of which they are composed, are well known, and can be definitely outlined as follows:

I. Carbohydrates.

1. Simple sugars.
2. Cane sugar, starches.
3. Cellulose.
Lignocellulose.
Pectin.
Gum.

II. Glucosides.

III. Tannins.

IV. Pigments.

1. Chlorophylls—green coloring matter of leaves.
2. Carotoids—coloring matter of leaves, flowers, and stems.
3. Anthrocyan—coloring matter of flowers, leaves.



PLATE III. A peat bog of the middle Carboniferous, as visualized by the Paleontologist. (From frontispiece of "Die Entstehung der Steinkohle", by H. Ponti, after a painting by W. Kranz.)

- V. Acids and their salts.
 - 1. Fats and oils.
 - 2. Lipoids.
- VI. Essential oils.
 - 1. Terpenes.
 - 2. Camphors.
- VII. Resins.
- VIII. Vegetable bases or nitrogen compounds.
 - 1. Amines.
 - 2. Alkaloids.
 - 3. Purines.
 - 4. Nucleic acids.
- IX. Proteins.
- X. Enzymes.

The total number of compounds embraced in this outline is large, but most of them are well known by the plant chemists, and all of them contribute to peat.

Plant substances may also be grouped according to their uses or rôle, such as :

- Framework materials,
- Living materials,
- Reserve and food materials,
- Protection materials, and
- Waste materials.

The framework material constitutes the cell-walls and other skeletal substances of the plant. It is made up of carbohydrate substances, such as celluloses, lignonecomplex, lignocellulose, pectins, and gums. The celluloses and lignonecomplex—in other words, lignocellulose or wood—constitute by far the largest bulk of the plant as a whole.

The living substances include protoplasm and enzymes. These are the most important and also the most complex substances in existence. All life depends upon them.

Reserve or storage substances accumulate in various parts of the plant to be available for the plant itself, or by its

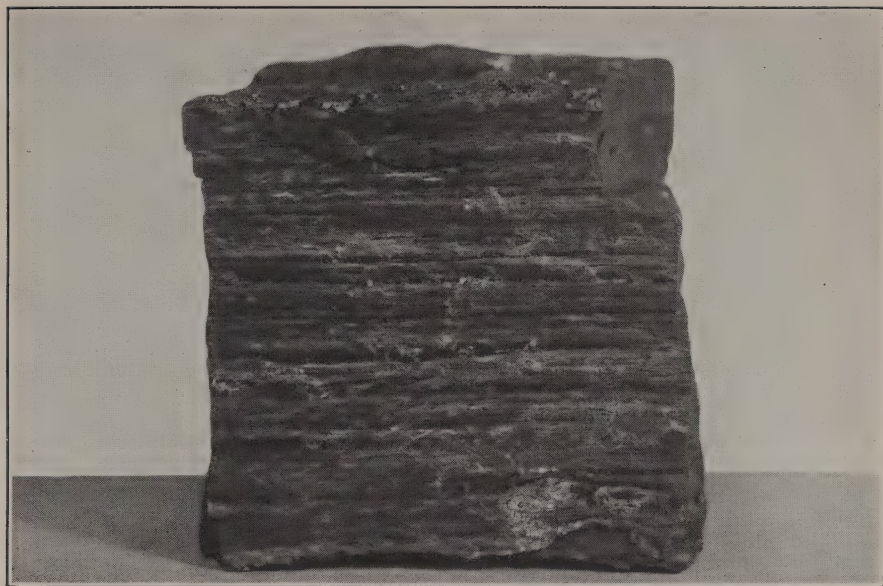


PLATE IV. A.—A lump of coal from the upper part of the Thick Freeport bed. The coal is composed largely of "dull coal", with but a few strips of bright coal or anthraxylon, represented by black bands. $\frac{1}{2}$ natural size. (After Thiessen and Voorhees.)



PLATE IV. B.—A lump of coal from the bottom of the Thick Freeport bed, composed largely of "bright coal" or anthraxylon. The black bands represent the anthraxylon, and the grayish bands the "dull coal". The bottom part of the black, about one inch in thickness, consists of bone coal. $\frac{1}{2}$ natural size. (After Thiessen and Voorhees.)

offspring, or seed for future use. Sugars, starches, fats, oils, and proteins serve as reserve substances.

Waste substances are substances thrown off as the result of life processes and are deposited in cavities, ducts, cells, or on the epidermis, and are of no further use. To these belong the resins, terpenes, camphors, and perhaps glucosides, and alkaloids.

Protective substances, as the name implies, serve to protect the plant from exterior forces or injuries such as weather, cold, heat, moisture and living organisms. In these are included the fats, oils, waxes, resins, and cuto-cellulose. They form coverings on leaves, stems, fruits, seeds, spores, and pollens.

HOW PLANTS CONTRIBUTE TO THE BOG.

During every growing season, plants grow new leaves, young shoots, flowers, seeds, pollens, and spores; wood and bark is added to the stems, besides, certain secretions such as gums, resins, and tannins, mostly products of disassimilation, are deposited in ducts and reservoirs throughout the plants. Every year, also, plants shed the leaves, blossoms, pollens, spores, part of the bark as a natural sequence of the life processes of the plant. Also twigs, branches, and trees are broken or torn down by the wind, ice, sleet, and snow. Trees or parts of trees die through injury, and sooner or later drop in a semi-decayed condition. Many trees, on account of the loose ground they live on, are not able to hold up, and gradually lean over more and more until eventually they lie flat on the ground, and sooner or later are buried dead or alive. Thus in the long run an equilibrium is maintained between growth and drop.

The dead material, as long as uncovered by water, undergoes a rapid decay, begun first by fungi and maintained by fungi and bacteria.

Several kinds of decay are recognized—namely, (1) complete decomposition with free access of air, in which no solid

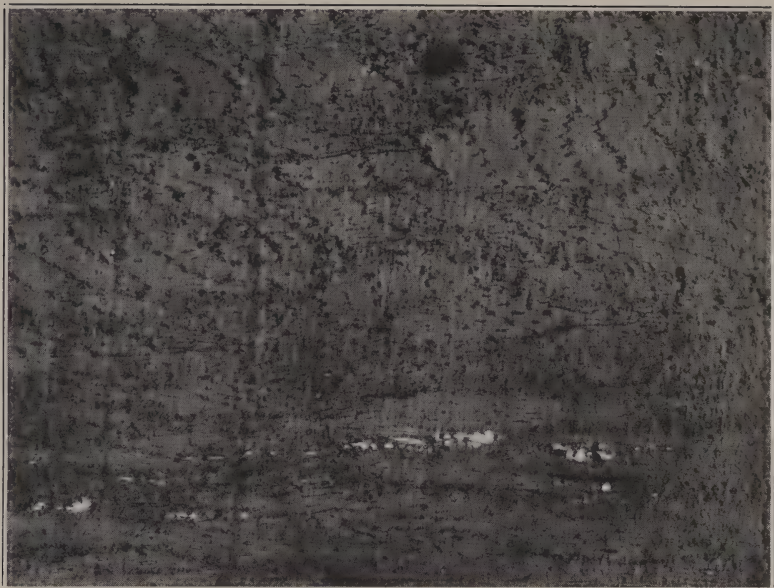


PLATE V. A.—Thin cross section of "bright coal" or anthraxylon, showing woody structure, much distorted and crushed. X200.

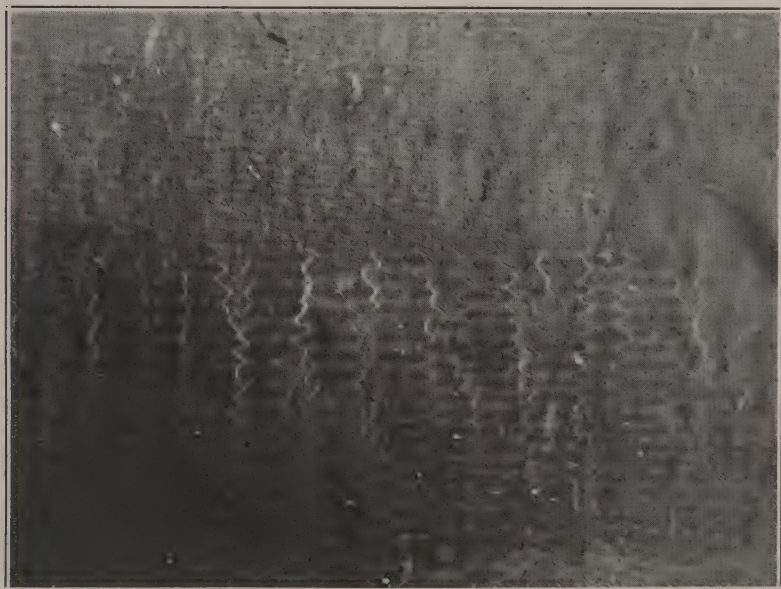


PLATE V. B.—Thin cross section "bright coal" or anthraxylon woody structure in varying states of preservation. X200.

matter remains that in any way could contribute to the formation of peat or humus. The main products are water and carbon dioxide. (2) Moldering or decay in moist conditions with somewhat checked access of air, through which earth molds and leaf molds are formed. Black earths or humus earths are the result of this type. (3) Putrefaction or decomposition in which air is excluded mainly by submersion under water. Decomposition under such conditions is very slow. And (4), peat-forming, a condition under which peat is formed. This process is a combination of all the types of decay.

Decay in the air is the initial and the most important step. Dead and partly dead trees, while yet standing, dead branches and twigs on living trees, trees broken down, branches broken down, leaves, bark, and other plant products are soon attacked by a large variety of fungi. These fungi soon transform these plant parts into a soggy mass and prepare it for the attack of bacteria. As long as the mass remains exposed to the air, decay proceeds rapidly, much of it decomposes completely, some of it remains in a semi-decayed condition. In this state much of it crumbles and much of this is transformed into a fine *débris*. In this condition the mass is sooner or later covered up by subsequent decaying vegetable matter, and becomes submerged below the water-level. Once in this position decay proceeds very slowly, partly on account of the exclusion of air and partly on account of the antiseptic condition of the mass caused by the decomposition products themselves. Slow changes, however, are taking place in the bog, and even at considerable distances below the surface. This is shown by the change of a more immature peat in the upper strata to more and more mature peat in the deeper strata. Also, living bacteria are found at all depths of the bogs. Also, gases, mostly methane, or marsh gas, are constantly being given off from the deposit, as every boy knows who has had the fun of

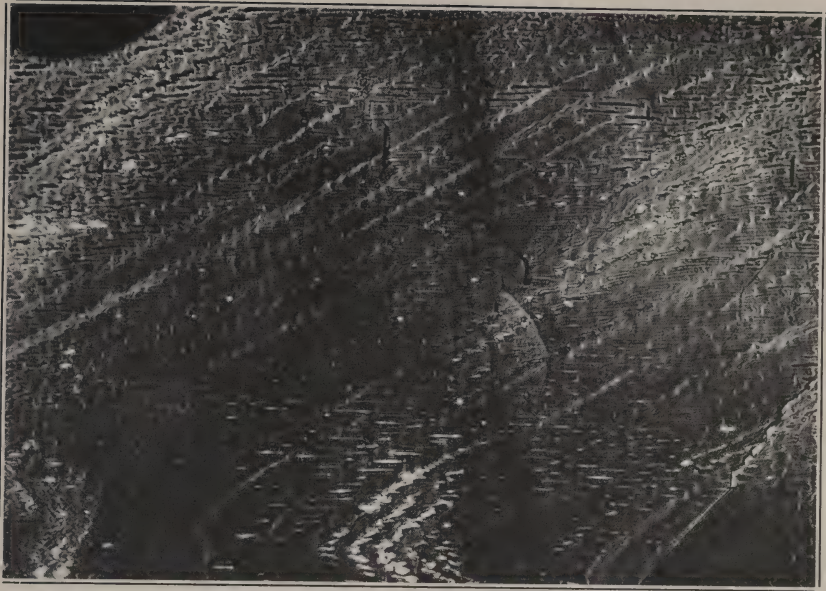


PLATE VI. A.—A thin cross section of "bright coal" or anthraxylon in which the woody structure is well preserved, though slightly distorted and much compressed. X200.

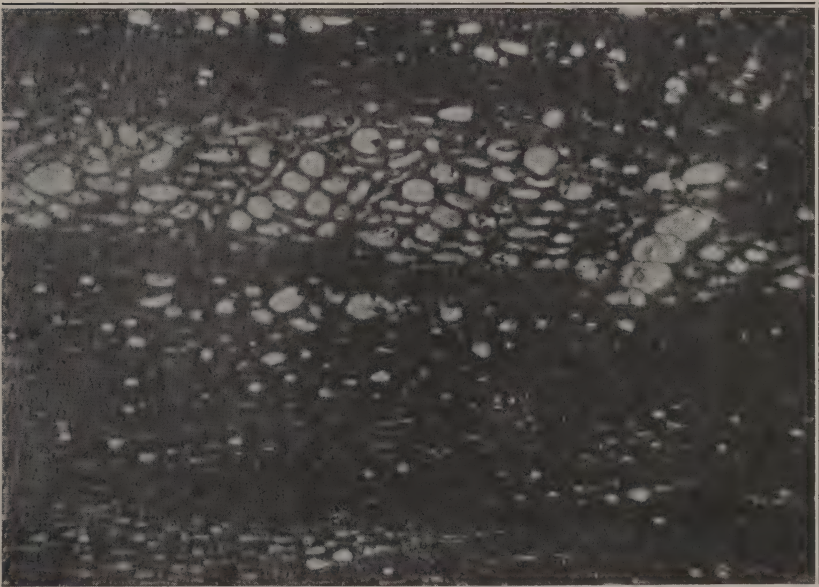


PLATE VI. B.—A thin cross section of "bright coal" or anthraxylon inclosing natural resin. Woody structure in varying states of preservation. X200.

wading in water with mud, containing plant matter, at the bottom.

Not all plant substances decompose with the same ease; in fact, some do not appear to be attacked at all by putrefying agencies, while others rot very quickly. The plant components that constitute the living part of the plant, and the plant foods and reserve substances such as the sugars, starches, and gums are relatively easily decomposed, and relatively little remains of these during ordinary rotting. The cell-wall components also vary greatly in the ease with which they rot or decompose. The hemi-celluloses, hexoses and pectins, decompose more easily than the celluloses, which are quite resistant. The cuto-celluloses are the most resistant to decay. The largest part, as already intimated, is contributed by the wood of plants. In recent years a considerable study has been made of decaying wood in connection with the paper industry, and this has been of great help in our study of coal. It must be remembered that in coal we are concerned with a substance derived largely from rotten wood. Wood is composed of cellulose and a lignin complex, the two forming the lignocellulose. In rotting wood the cellulose disappears fairly rapidly, while the lignin complex or certain parts of the lignin complex remain. And it is this part that mainly contributes to peat.

Those substances which we have called the protective substances are all very resistant to agencies of decay. To them belong, as already said, cuto-cellulose, wax, fats of higher molecular weight and resins. The cuticles of many plants, the spore-exines and pollen-exines, are largely composed of such substances, and undergo but little chemical change. The waste products in general are disassimilation products, and no longer available as foods are also not putrefiable. To these belong the resins, terpenes, and alkaloids. Because these substances undergo little or no decomposition, and since those substances that form the bulk of the plant mass undergo considerable decomposition, the former substances



PLATE VII.—A thin cross section of dull coal, Pittsburgh Bed, at a low magnification. The strips in light gray represent thin strips of "bright coal" or anthraxylon; the darker strips between these represent the attritus. X10.

remain in relatively much larger percentages than found in the plant originally. It is thus seen that a selection of the more resistant substance is going on all the time, and the more resistant the less is their loss, and that the more and more resistant substances accumulate proportionately faster than the least and the less resistant.

FORMATION OF COAL BEDS.

It has been shown how many peat beds were laid down, what material contributed to them and what became of them. It is now generally understood that coal beds were formed in a somewhat similar manner. The strongest argument for assuming this analogy is that they are alike—constituent for constituent.

PERIODS OF COAL FORMATION.

There were three periods in the earth's history with conditions favorable to the accumulation of plant material which has since been converted into lignite, brown coal, bituminous coal, or anthracite. By far the most extensive accumulations occurred towards the close of the Paleozoic era. At this time all the important coals of eastern North America, Europe, and China were laid down. The second period occurred during the Cretaceous times, in which the Rocky Mountain coals were formed. The third period occurred during the Tertiary, when the brown coals of Europe and lignite in an area chiefly west of the Rocky Mountains were formed. Some coal is found in the Triassic of eastern North America, and in small quantities in beds of other ages in various parts of the earth.

A coal bed usually rests upon a bed of fireclay. Coal beds vary in thickness from a mere film to many feet. It is common that the vertical continuity of a bed is interrupted by layers of shale or bone coal. Overlying the bed there is frequently a roof of shale, which is a consolidated mud; but sandstone roofs are not uncommon.

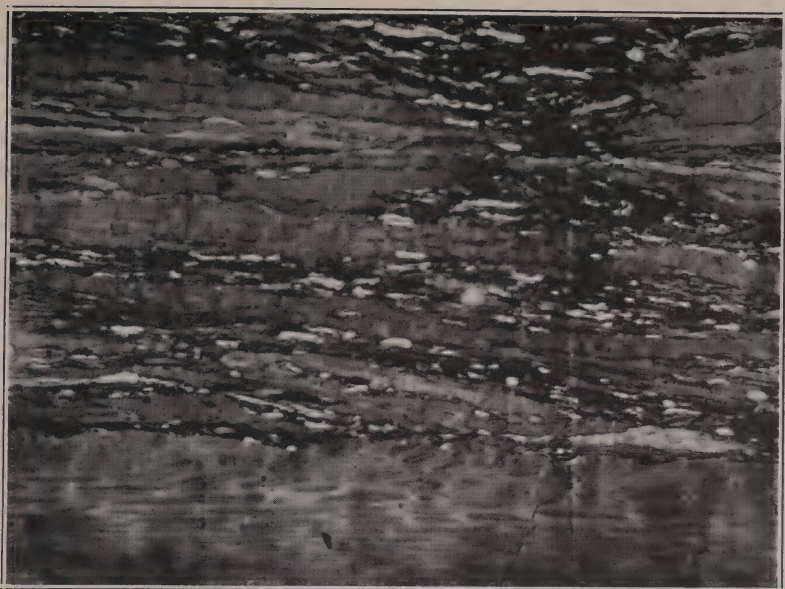


PLATE VIII. A.—A thin cross section of "dull coal" at a higher magnification. The upper part consists largely of attritus and thin bands of anthraxylon; the lower part contains a thin band of anthraxylon with well preserved plant structure. X200.

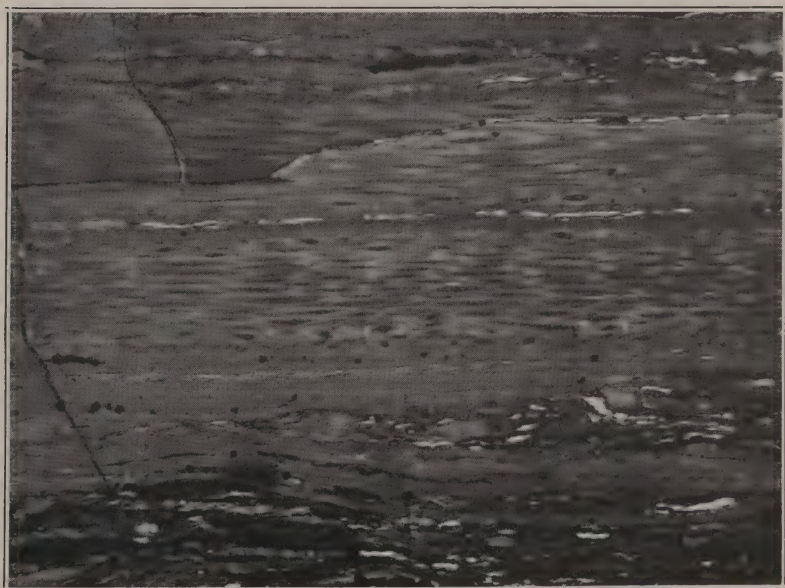


PLATE VIII. B.—A thin cross section of "dull coal" with a thin band of anthraxylon with well preserved plant structure but much compressed. X200.

KINDS OF PLANTS THAT CONTRIBUTED TO COAL.

The kinds of plants that prevailed during the Carboniferous period belonged to totally different families—families now extinct—or represented only by small herbaceous plants (Plate III).

The main representative plants of the Carboniferous age were the Calamites or ancient horsetails; the Lepidodendrons or the ancient Lycopods, to-day only represented by the club-mosses or ground pines and selaginella; the Sphenophylls, now totally extinct; certain Cycadad-like Gymnosperms and Cordiales, related to our present conifers. Ferns were not well represented, and flowering plants were probably not represented at all.

The plants that contributed to the Cretaceous and Tertiary coals were more like the plants of to-day. A large proportion of these plants appear to have been conifers, closely related to the present bald cypresses, red cedars, sequoias and others. But flowering plants, such as the oak, birch, plantain, and beech, had also appeared.

While the kinds of plants differed considerably in type and species, the chemistry of the ancient plants was probably not different from those of to-day, and their decomposition resulted in similar products.

It has been found in most cases that the ancient peat bogs were formed in a subsiding region of the earth's crust. The swamp began probably with a moist condition, then gradually became wet, and then gradually changed into an aquatic condition. While in the aquatic condition the inflowing water carried in silt and sand, and finally the bog was covered with rock-forming material which in time formed shale and sandstone. The peat mass was gradually compressed more and more, and deprived of its high water content. As a result of the compression, but in particular due to the elimination of water, and to its colloidal nature, the mass gradually hardened, as such substances invariably do when deprived



PLATE IX.—Thin cross section of dull coal, Pittsburgh bed, largely composed of attritus, with a few very thin bands of anthraxylon. The attritus is composed largely of spore matter, some highly carbonized particles, and some woody degradation matter. X200. (After Thiessen and Staud.)

of water. There was thus a gradual change from peat into lignite, from lignite into sub-bituminous coal, then into bituminous coal as time went on, and, in the case where greater earth movements prevailed, into anthracite.

COMPILATION OF THE COAL BED.

All ordinary bituminous coal on close examination is found to be highly laminated and compiled of various layers and sheets of coal differing from one another in color, texture, and mode of fracture, and varying greatly in thickness (Plate IV). In general, two kinds of layers are recognized, apparently alternating and standing in sharp contrast to one another: one is of a jet-black pitchy appearance and compact, breaking with a definite concoidal fracture; while the other is somewhat grayish in color, of a dull appearance and less compact. The former is generally designated as "bright coal", and the latter as "dull coal". The bright coal consists of lenticular masses embedded in the dull coal. The dull coal is further sublaminated into very thin laminae of bright coal embedded in a granular dull coal or attritus (Plate VII).

These characters are easily observed in any block or lump of coal; but usually a single block of coal is not large enough to reveal the lenticular structure of the thicker bright-coal strips. Of the smaller and thinner ones, however, this is well shown.

In comparing a lump of coal with a lump of peat we find the same kind of components in each; every kind of component found in the one is also found in the other. In order to discover the parallelism or similarity of the two it is necessary to cut thin sections of the coal and examine them under the microscope.

PREPARATION OF THIN SECTIONS.

A thin section of coal is made much in the same way as a thin rock section is made. A selected piece of coal, having

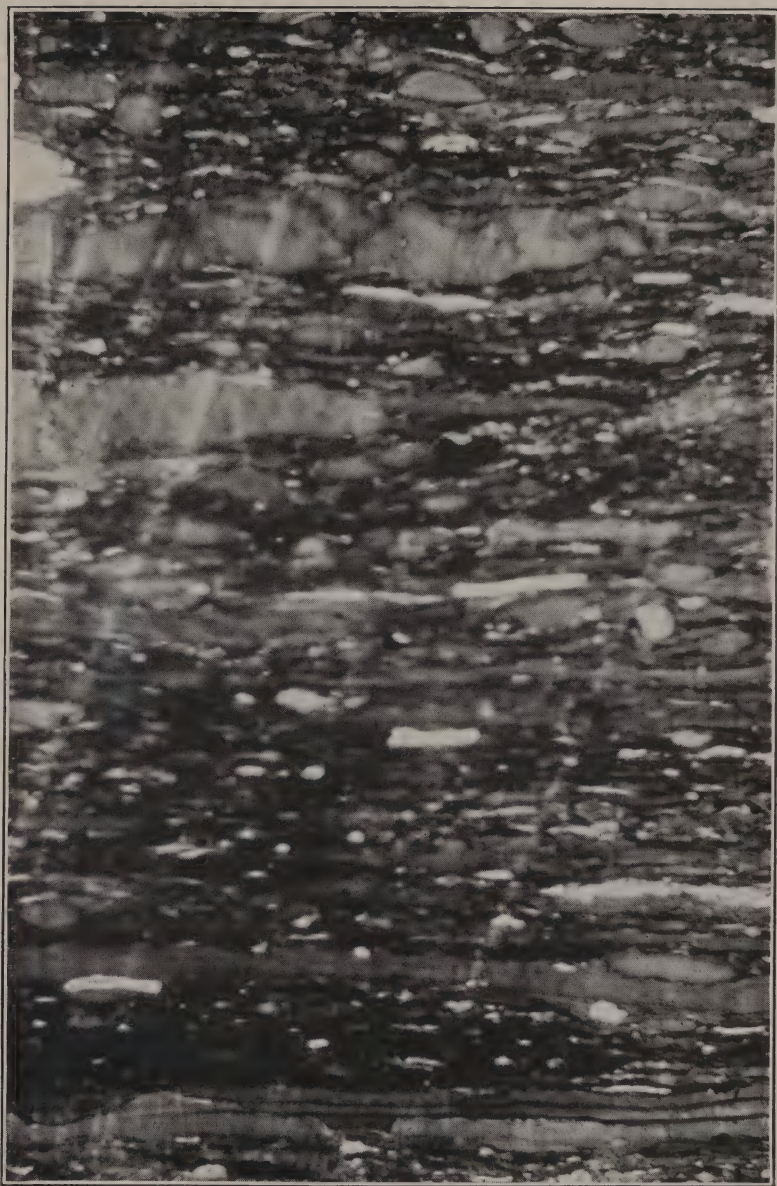


PLATE X.—Thin cross section of "dull coal" Redstone bed, composed of attritus, consisting largely of woody degradation matter and some spore matter. X200. (After Thiessen and Staud.)

a face approximately $\frac{1}{2}$ by $\frac{3}{4}$ inch, and $\frac{1}{2}$ inch in thickness, is carefully polished on one side, either perpendicular to the bedding or parallel to it, first by coarse grinding, and next by rubbing on a very fine hone. After this is done it is glued, with a mixture of three parts of Canada balsam and two parts of marine glue brought to a correct consistency by previous heating, to an object slide. When this is done the preparation is ground down on an ordinary lapidary's wheel to the thickness of about $\frac{1}{50}$ -inch. It is then further ground down by rubbing on a fine hone until transparent. Such a section reveals a marvelous array of beautiful colors, from yellow to deep red. The coal in such a section has not been changed in the least, and reveals all the constituents in the natural condition.

BRIGHT COAL.

In examining a layer or strip of bright coal, no matter how thick or from what part of the coal, or from what coal bed, it reveals a structure derived from that of wood (Plates V and VI). No sheet or layer of bright coal of any thickness has yet been found that does not reveal this structure. Often we find the woody structure so well preserved that it is possible to recognize the kind of plant from which it came. Often also such pieces of woody coal still include the natural resins of the plant (Plate VI B). It must be observed, however, that the tissues thus revealed in the bright coal have been much compressed and squeezed together. Sometimes the mass has become so much pressed together that it has become quite homogeneous, and the structure is then fairly difficult to reveal. We must conclude, therefore, that these layers or sheets of bright coal are derived from larger pieces of wood. These components being derived from wood, but being no longer wood, but coal, we shall call them "anthraxylon", meaning coal from wood. We have then in the anthraxylon strips or masses, components parallel to the larger woody pieces of peat.



PLATE XI.—*Equisetum arvense* or common horsetail. (1) three fertile shoots, showing the cycles of scale leaves at the joints and the terminal cones with numerous sporophylls, that of (a) being mature; (2) a sterile shoot, showing branching; (3) a single sporophyll bearing sporangia; (4) view of sporophyll from beneath, showing opened sporangia; (5, 6, 7) spores with elators. (After Coulter and Wossidlo.)

DULL COAL.

Turning now to the dull coal, and in examining a section of it at a lower magnification, say 10 diameters (Plate VII), it is shown that it is composed of thin strips of bright coal embedded in a granular mass, the "attritus". In examining these thinner strips of bright coal at a higher magnification it is again found that they also show woody structures (Plate VIII). As all of them show this structure more or less well preserved, and as they are of the same order as in the larger strips, we come to the conclusion that they represent smaller fragments of wood turned into coal, and hence are smaller strips of anthraxylon. These again represent the smaller splinters or fragments of woody matter in peat.

The bottom coal of a coal bed is usually composed of a relatively large amount of anthraxylon, and a small amount of attritus (Plate IV B). But in going from the bottom to the top of the bed the amount of anthraxylon, in general, decreases, while the relative amount of attritus increases, so that the top coal usually consists entirely or almost entirely of dull coal (Plate IV A), while the bottom coal consists largely of bright coal (Plate IV B). In some cases the anthraxylon or bright coal disappears entirely at the top, and in that case the coal is simply called a "cannel coal". (Plate XXI).

THE ATTRITUS.

The granular matter or attritus is also called the ground-mass, as every other component is surrounded by it or embedded in it. It is a complex substance, being composed of a considerable number of constituents derived from various parts and organs of plants. (Plates VII, IX, X, XV, and XVI).

The attritus is the rubbish pile or refuse pile left by the decaying plants. It must be expected, therefore, to find in it, besides the woody and cellulose degradation matter or humic matters, other substances quite resistant to decay.



PLATE XII.—Two herbarium specimens of *Lycopodium obscurum*, a common ground pine or club moss with cones. $\frac{1}{2}$ natural size. (After Thiessen and Staud.)

To these substances belong the outer coverings of spores and pollen grains, cuticles, waxy coverings of leaves, stems and fruits, resinous matter, certain oils or fats, and waxes contained in the tissues. Besides these there is a long list of substances in plants that more or less resist putrefaction, such as tannins, alkaloids, terpenes, camphors, and others. Many of these, however, are so scattered throughout the plant in such small quantities that they ordinarily escape observation under the microscope. But when the plant decayed, much of this remained behind with the rubbish, and must still be there with the rest of the remains. These are some of the little things that are so easily overlooked, and when coal is heated we wonder where all of the products given off come from.

Some of the constituents of the attritus like the humic matter, spores, cuticles, and resins form a fairly important rôle in the general character of the coal and require further mention.

HUMIC MATTER.

The humic matter may (Plate X) be derived from the woody and cellulosic tissue, from bark, cork, cortex, leaves, and other plant substances. Much of it has lost its identity, but much of it has retained some of the original cell structure.

SPORE-EXINES.

The spore-exines are the most obvious constituent in coal, and are easily seen on account of their clear yellow color and transparency. They are present in every coal, more in some than in others (Plates XIV, XV, XVI, and others). What are spore-exines?

Spore-exines are merely the shells, or outer walls, or coverings of spores. The easiest way to illustrate what spores are is to refer to the ordinary ferns, so often grown in pots as house plants. On the under surface of the leaves of the ferns, rows of dots are visible at most any time of

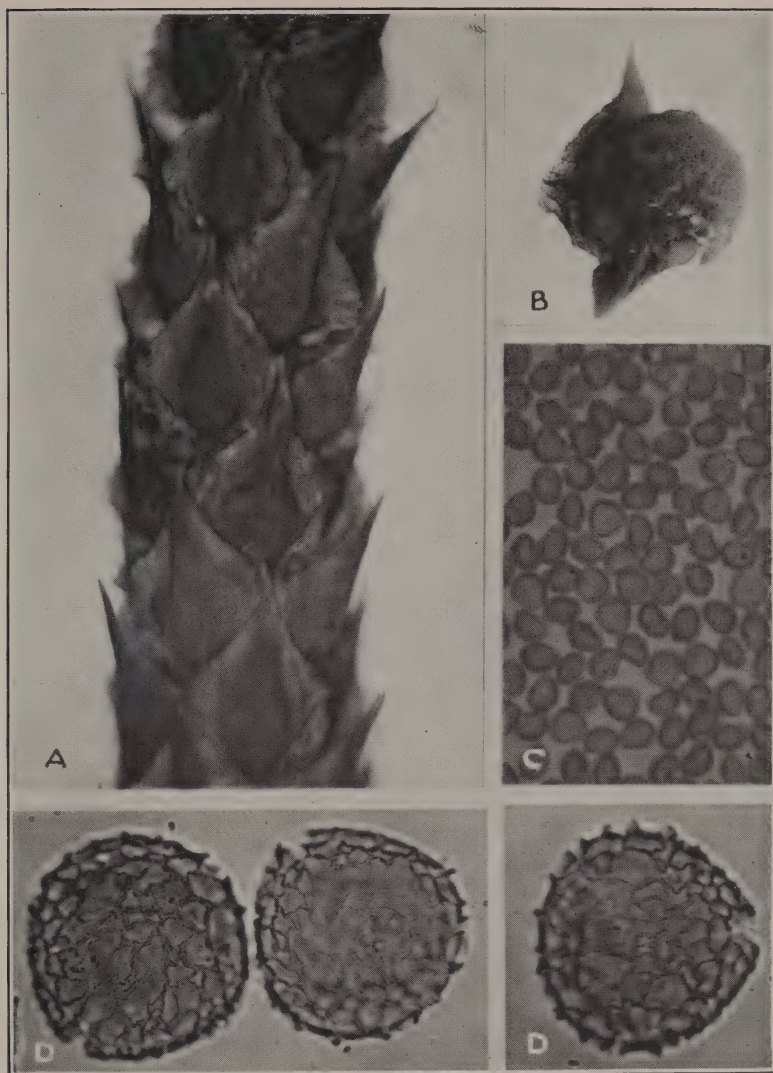


PLATE XIII. A.—Part of one of the cones of plant shown in Plate XII. X20.

PLATE XIII. B.—One of the sporophylls of the same removed, showing globular sporangium underneath, filled with microspores. X20.

PLATE XIII. C.—Spores from the same X200.

PLATE XIII. D.—Spores of the same at a high magnification showing sculpturing of the spore exine. X1000. (After Thiessen and Staud.)

the year. When the fern is handled at certain periods a fine dust is seen to come off the leaves having these spots. This dust consists of the spores of the fern. Unfortunately, ferns of this type did not contribute materially to the coal flora of the Carboniferous Age, and therefore furnish a poor example as to the kind of plants contributing to coals.

The common horsetail or *Equisetum* (Plate XI), and the club moss or *Lycopodium* (Plate XII) of both of which there are a number of species, and which are direct descendants of plants that contributed largely, if not the most, to the coal substances, are much better examples to illustrate the origin of spores in coals as well as the main or woody and other substances in coal.

The present common horsetails are the lingering remnants of the *Calamites* (Plate III), a once abundant vegetation which largely contributed to coal. Horsetails grow in moist or in dry places, sometimes in great abundance. Early in the Spring a slender stalk shoots up from a slender rhizome, bearing on the end a club-shaped shoot (1, Plate XI). This is the spore-bearing part of the commonest of the horsetails, *equisetum arvense*. Soon a large amount of yellow powder may be seen to come off this cone when lightly touched. This yellow dust again consists of the spores (5, 6, 7, Plate XI). In a short time these spores are all shed and the stalk again disappears, shortly to be followed by other shoots which develop into small tree-like or bushy plants (2, plate XI). These are the plants of the horsetail as ordinarily known, and do the chlorophyl work of the plants.

The *Lycopodia* (Plate XII), popularly known by the name of "club mosses", or ground pines, and whose ancestors, the *Lepidodendrons*, also contributed largely to the coals, are good examples to illustrate what is meant by microspores and megaspores.

Club mosses, or ground pines (Plate XII) are small tree-like or bushy plants, hardly more than a foot high, although

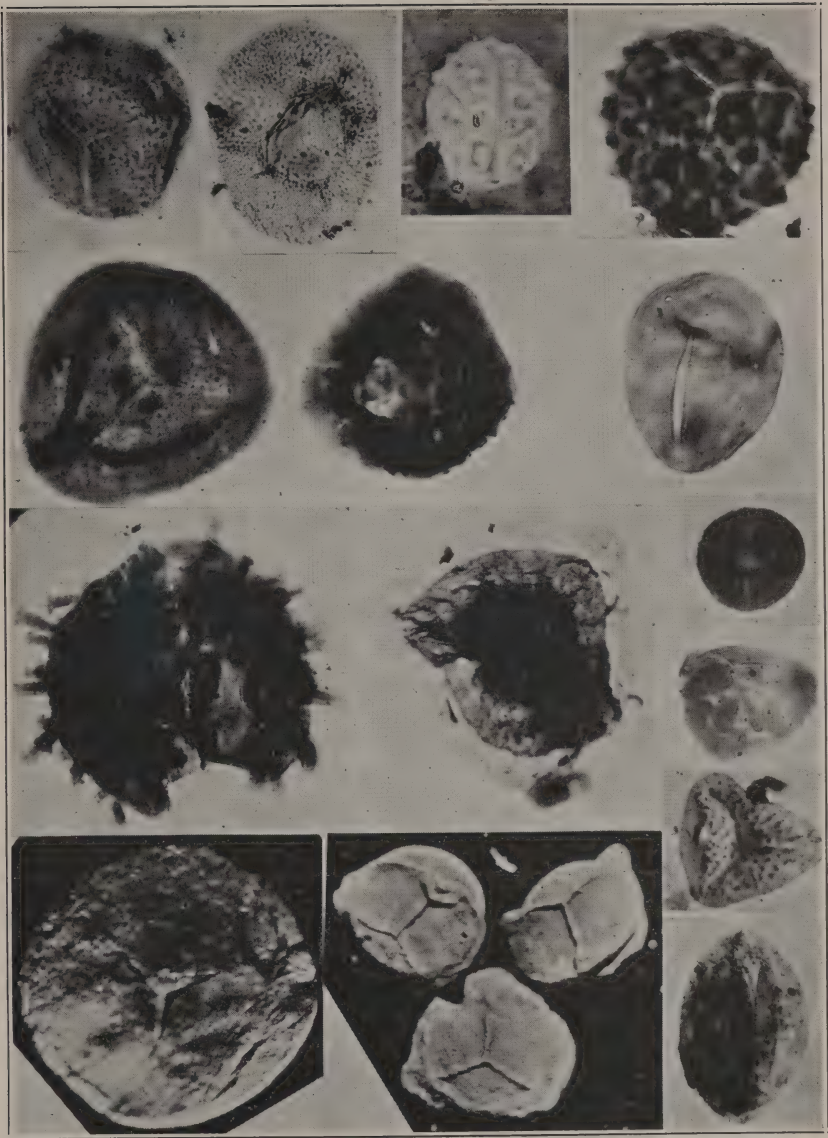


PLATE XIV.—A few of the different types of spores found in coals.

their ancestors (the *Lepidodendrons*, Plate III), during the Carboniferous times, grew to be large trees. The stems and branches are clothed with small leaves, having a moss-like appearance. Often the erect branches are terminated by conspicuous cones. These cones have the appearance of clubs, and from that and their moss-like appearance they get the name of club-mosses. The cone (Plate XIII A), it is seen, consists of thick and closely overlapping leaves. These are the sporophylls. On the underside of each of these is a globular sack (B, Plate XIII), the sporangium, each filled with thousands of spores (C and D, Plate XIII). It is the source of the lycopodium powder used for various purposes and for sale in drug stores. In these cases the spores are all of the same size, and small, and are usually designated by the term of "microspores". There are found in the coals certain large spores called "megaspores". The origin of the megaspores is well illustrated in some of the *Lycopodiales*, particularly in the genus *Selaginella*, which grows in warmer climates, and is locally only found in the greenhouse. Although more delicate, it looks very much like lycopodium. Certain terminal branches bear cones just as lycopodium; but the important difference is that the sporophylls in the upper part of the cone bear, as in *Lycopodium*, numerous small or microspores, while the sporophylls in the lower part of the cones each bear only four large or megaspores.

In the last stages of the development of the spores, the last two divisions of the mother cells occur simultaneously, giving rise to four cells which develop together into four mature spores, and are therefore called "tetraspores". This position in fours lends each spore a characteristic triradiate mark, called the "tetrasporic mark" (Plate XIV), which identifies it as a spore. Every spore consists of the living or protoplasmic part, which is enclosed by a thin membrane, the *entene*. The whole is covered by a thick-walled outer wall or *exine*. The protoplasmic or living part decays

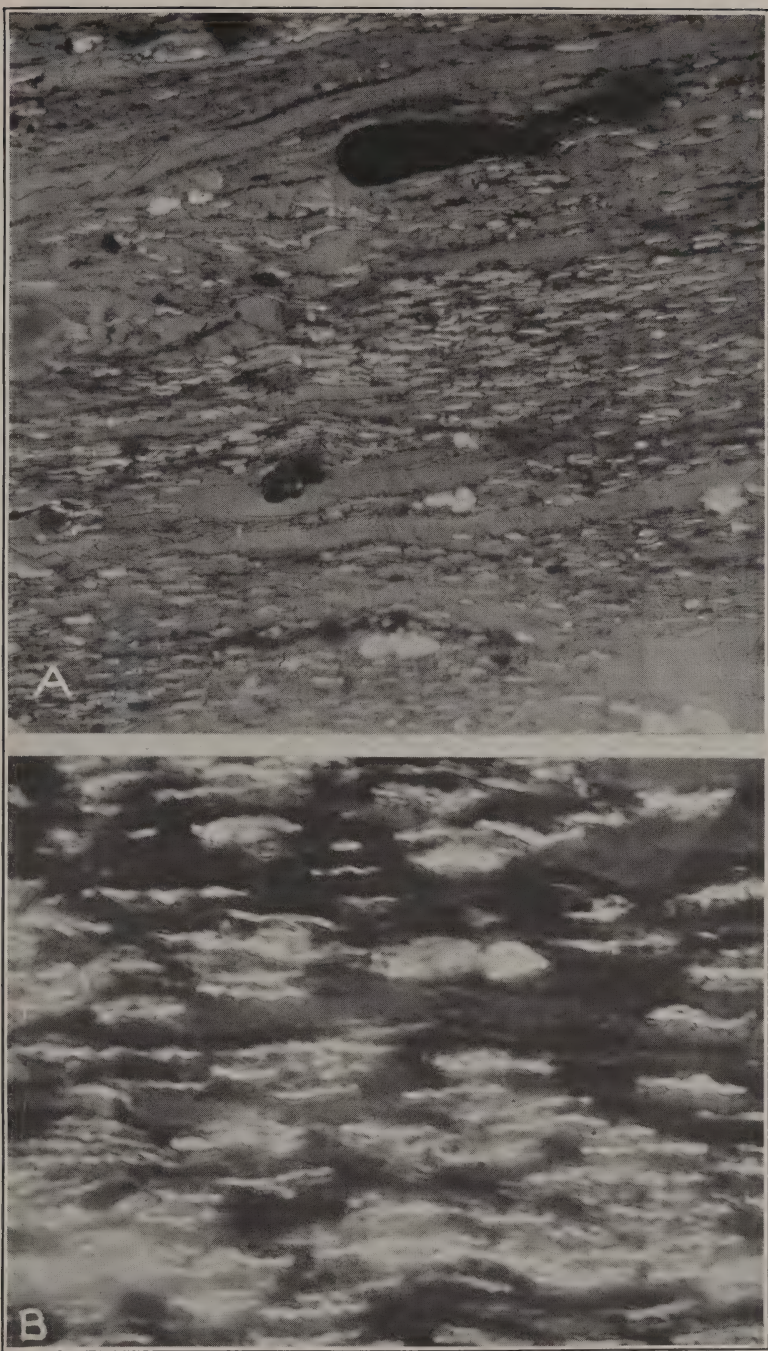


PLATE XV. A.—Thin cross section of Pittsburgh coal showing attritus rich in the "Pittsburgh Spore". X200.

PLATE XV. B.—Part of the same at a high magnification, showing crinkled appearance of Pittsburgh Spore in cross section. X1000. (After Thiessen and Staud.)

readily, and contributes nothing, or at the most but little, to the coals. On the other hand, the outer walls or exines are composed of resistant substances like waxes, oils, and cuticellulose, and withstand all the coal-forming processes, persist well preserved in the coals, and have contributed a considerable part to them.

A fairly large number of different kinds of spores are found in all the coals taken together (Plate XIV) but in any one bed relatively few kinds are present. In other words, each coal bed has only a few kinds of spores, and one or two, and sometimes three kinds, are found predominating in that bed only, and nowhere else or only sparingly in another bed or other beds. Sometimes there may be quite a number of different kinds in a bed, but one kind only predominates in that bed. The Pittsburgh coal bed, for example, has a relatively large number of spores and also a considerable number of different kinds of spores; but the largest number, by far, is represented by one kind, a rather small spore with a complex sculpturing (Plates XV and XVI). And as this spore is found in no other coal, it is an easy matter to distinguish a Pittsburgh coal from any other coal. In the same way coals from other beds may be distinguished.

RESINS.

A large number of plants, such as the pines, spruces, tamarack and many others, contain a considerable amount of resinous matter stored up in resin-ducts and reservoirs. The amount of these resins varies from a fraction to as high as ten per cent. of the living plant. In the lignites it is easy to find these resinous matters still intact in the wood and other tissues exactly where they would be expected to be found (Plates XVII and XVIII). They are also found in the attritus of the lignites, the wood or other tissues simply having decayed, while the resins dropped out undecayed. (Plate XIX). The identity of the resins in the

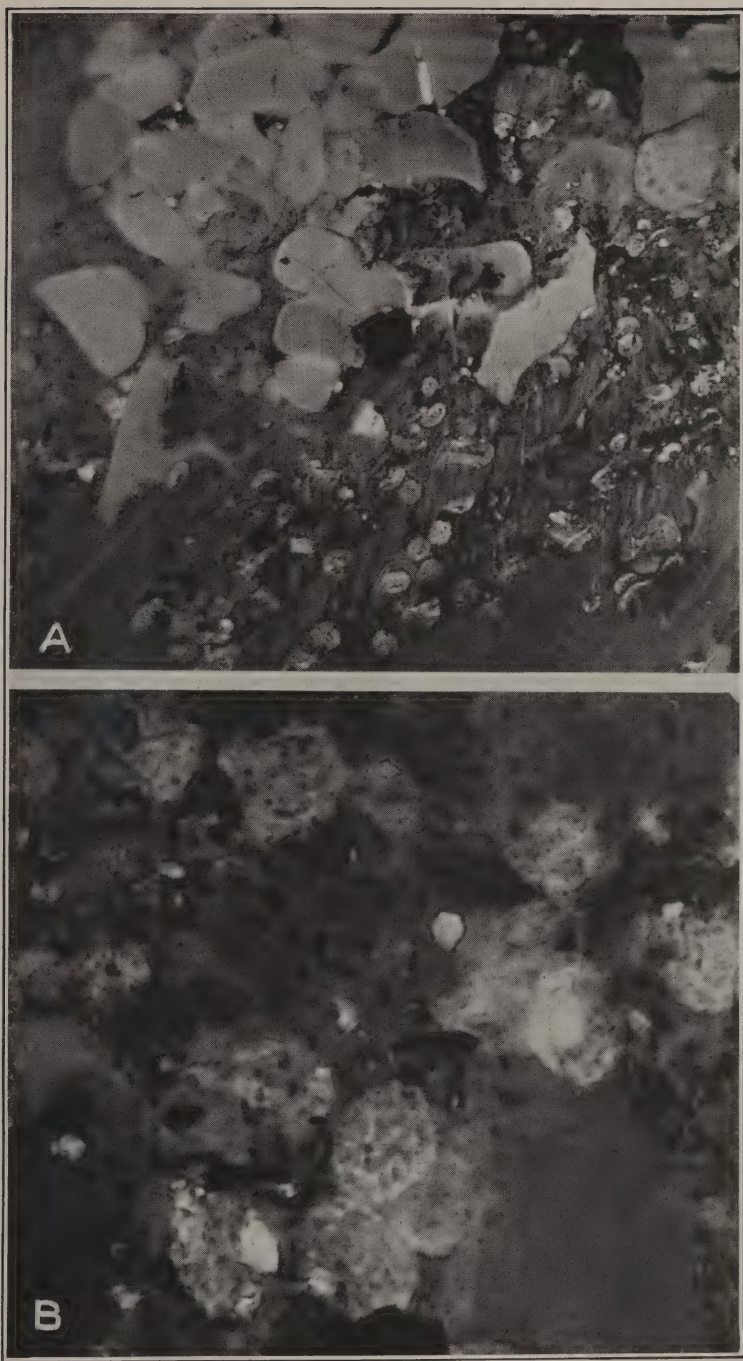


PLATE XVI. A.—Thin horizontal section of Pittsburgh coal, showing attritus with spores and resinous and humic matter. X200.

PLATE XVI. B.—Part of the same thin horizontal section shown in A, more highly magnified, showing characteristic appearance of the "Pittsburgh Spore" in horizontal section X1000. (After Thiessen and Staud.)

lignites is therefore certain. In the woody tissues of the bituminous coals, resinous-looking inclusions are also found (Plate VI B). In this case it is also safe to assume that they are the natural resins of the plant which gave rise to that part of the coal. In the attritus of the bituminous coals, also in numerous sections, resinous-appearing bodies usually form a considerable part of it (Plate XX); and by analogy we assume that they are natural resins of some coal-forming plant which rotted away, leaving the resins behind undecomposed.

The lignites furnish an interesting study as to how the more resistant substances accumulate in large proportions. In some cases lignites consist of 50 per cent. or more of resinous matter, the woody substances having decayed to such a proportion as to increase the resinous matter from a few per cent. to fifty per cent. and over (Plates XVIII and XIX). Something like this has also taken place in the bituminous coals. Many sections are met with in which the resinous matter has been concentrated so as to form more than half of the coal in the section.

CUTICLES.

As we all know, all leaves, fruits, and green stems of plants are covered with cuticles to protect them from insects, bacteria, moisture, or other injury. These cuticles are frequently covered with a layer of wax. The thickness of the cuticles and that of the waxy covering varies considerably, but in some plants the latter is so thick that they have become of industrial importance. Carnauba wax is a good example. The substances forming the cuticles are very resistant to decay. Cuticles are a common component in peat, due to their resistant nature. Similarly, in coals a considerable amount of cuticular matter is always found. In thin sections they appear as bright golden yellow bands. They usually go in pairs, and commonly have serrated



PLATE XVII.—Thin cross section of Anthraxylon of Dakota lignite, being a cross-cut of its woody tissue, showing annual rings of wood, well preserved autumn wood, poorly preserved spring wood, and natural resin in situ. X200.

borders. In some sections cuticles compose a considerable part of the coal substances.

In a retrospect we see then that coal contains every constituent that remained in peat—namely, larger and smaller constituents derived from wood, woody degradation matter, cuticles, spores, pollen grains, and resins. Besides these, plants contained many other substances that were contributed to the deposit, but since they were present in small quantities in the plant, and furthermore were broadly distributed in the plant, they have been lost in the rubbish and are not recognizable in the coals under the microscope. That some of them are present in coal is shown by certain distillation products.

KINDS OF COAL.

It now remains to discuss what constitutes the different kinds of coal—namely, lignite, sub-bituminous, bituminous, anthracite, cannel coal, and boghead coal. From what has already been said it should be clear what are the differences in general in lignite, sub-bituminous coals, bituminous coals, and anthracite. They represent merely stages or steps in the coalification processes, in which peat represents the first and initial stages, the lignite of the Cretaceous and Tertiary periods, many thousands of years old and the bituminous coals of the Paleozoic era, many million years old, each being separated by very long time intervals. Furthermore, there are no hard and fast lines to be drawn between them, all grades and shades of transitions from one into the other are found. In some of the Western coals, transitions from low-rank lignites to semi-anthracite are found in one and the same bed. The differences in different ranks of coals are not caused by different kinds of materials that contributed to them, but caused by agencies of coalification. Geologists usually name time, pressure, and temperature as these causes. Time, it should be remembered, is in itself no agent; but it



PLATE XVIII.—Thin cross section of Dakota lignite, being tangential cut of the woody structure, showing natural resins in the ray cells. The cells other than the resin cells have been much decayed and compressed. X200.

is the duration during which an agent has an opportunity to act. It is believed that slow spontaneous chemical reactions are going on in most complex organic substances. In a short period the result of such reactions would be negligible; but over periods of thousands of years, or even millions of years, the total results must be large. Time was probably the greatest factor in the coalification process; but other factors must also be sought, because we have coals of the same age, and, as has been stated, coals in the same bed of different rank. Pressure is the factor that is most often thought of, because we find coals of higher rank in regions that are supposed to have been submitted to very high pressures. Earth movement, earth uplifts, and earth thrusts are said to be accompanied by high pressure. Coals in such regions, anthracite, for example, and coals of high rank in other parts of the country, are invariably associated with earth folds or are found in mountainous regions—in other words, in regions that have been subjected to high pressures. Experimentally it has not been demonstrated that pressure can change organic substances chemically, although it is known that pressure modifies reactions. We must look, therefore, to some other cause.

We all know that when we want to hasten a reaction we do not submit it to pressure, but warm it or heat it. Cooking a meal, for example, is merely a physical change accompanied by some chemical changes in the food brought about by slightly higher temperature. It is doubtful whether a pressure of hundreds of atmospheres would bring about changes as noticeable. It is therefore likely that the greater changes that have occurred in the anthracite or semi-anthracite over the bituminous coals, or the greater changes of sub-bituminous coals over the lignites in the same age or bed, are brought about by slightly higher temperatures. These temperatures need not have been very high. Long time would bring about a relatively great change at but a

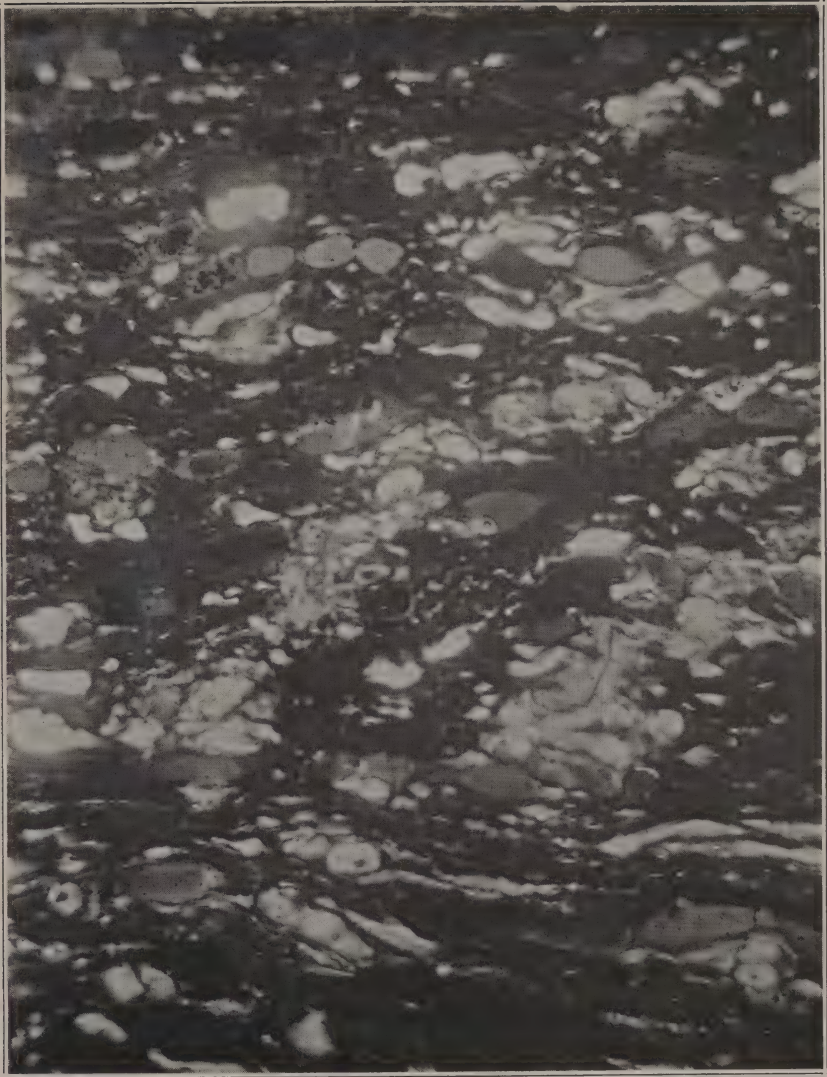


PLATE XIX.—Thin cross section of Montana lignite, showing resinous matter in the attritus; two kinds are noticeable, light and a dark colored. X200.

slightly higher temperature. It has been shown that higher temperatures prevail in regions of the earth's crust, where movements are in progress, than in regions at rest. That coals in regions that have been subjected to stress and earth movements are of higher rank than those found in undisturbed regions is without question. Pressure probably also caused the anthracite and other coals to be more compact and of a higher specific gravity.

CANNEL COALS.

Cannel coals owe their differences as compared with ordinary coals to differences in origin and differences in the plant substances that compose them. The best cannel coals are composed almost entirely of spore matter (Plate XXI). It is believed that cannel coals were also formed in bogs, but that these were entirely of the aquatic type, that is, they were in form of a shallow lake. The aquatic plants growing in this bog bore numerous spores, and while all the rest of the plant substances decomposed, the spores being the most resistant parts, remained to form a deposit composed almost entirely of them. Some cannel coals also contain a considerable amount of the woody degradation matter of the plants, just enough of the humic débris having been left to make an impure cannel coal.

In conclusion, then, to look back upon the problem of what coals are actually composed of, we can do nothing better than to consider the chemical composition and nature of plants to which they owe their origin. The chemistry of plants and their products are quite well known, but unfortunately, before the plant substances were formed into coal, they were subjected to a process of decay and putrefaction. What the chemical nature of the substances was after that process was completed is not known. Furthermore, during the coalification processes further changes took place, removing the substances still further from their original

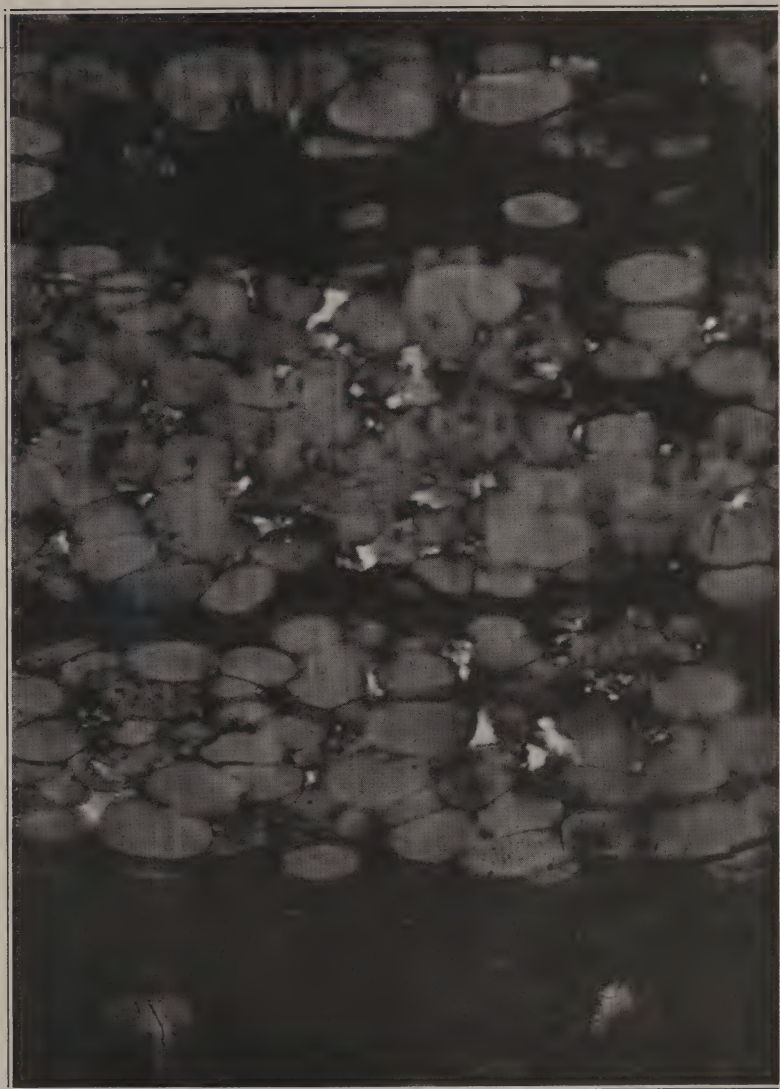


PLATE XX.—Thin cross section of Upper Freeport coal, showing thin layers of resinous matter.

composition. All that we do know, therefore, is where certain constituents came from, and what their original composition was. This, however, gives us some idea as to what they may be and what they cannot be in the form of coal.

Microscopic Laboratory,
Chemical Division,
Pittsburgh Experiment Station,
Bureau of Mines,
June 30, 1924.



PLATE XXI. A.—A lump of cannel coal from Cannelton, Beaver County, Pa. Notice the absence of layering. $\frac{1}{2}$ natural size.

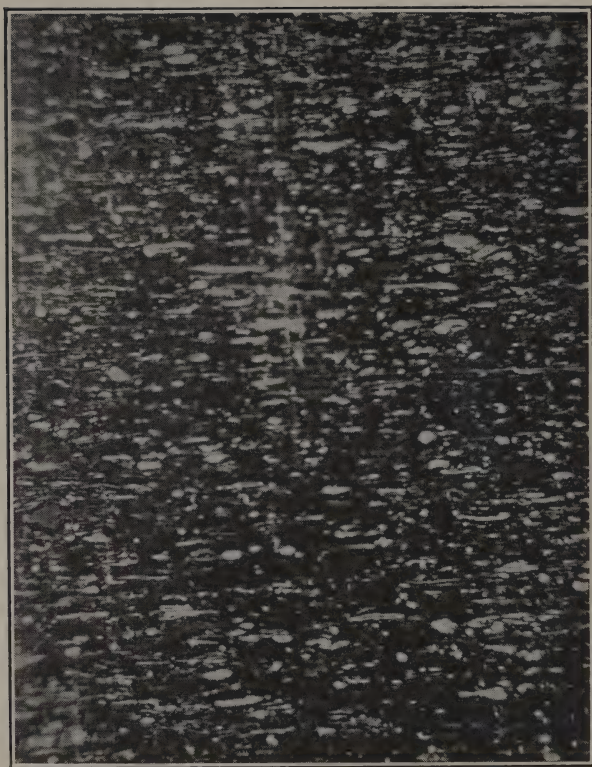
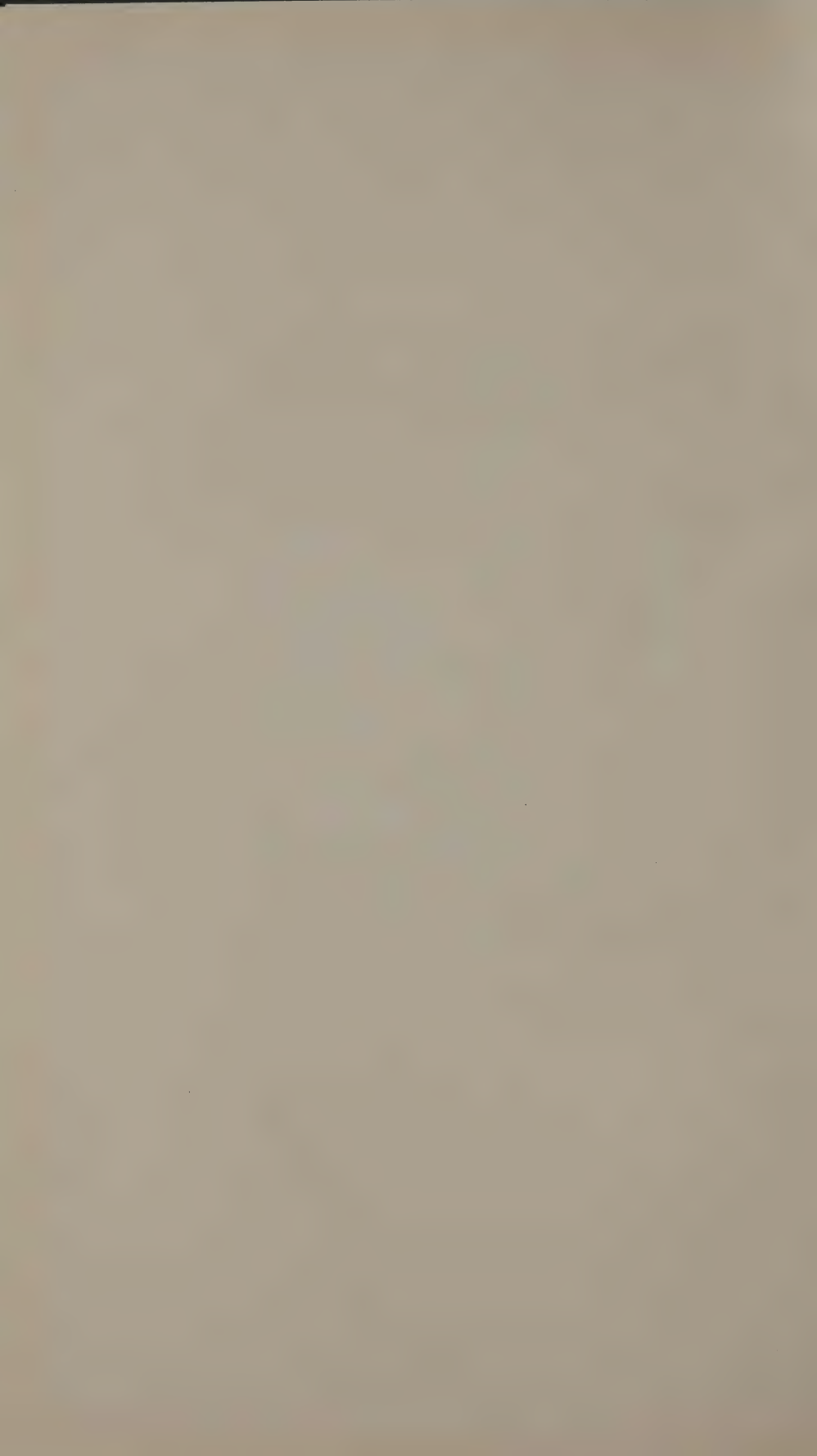
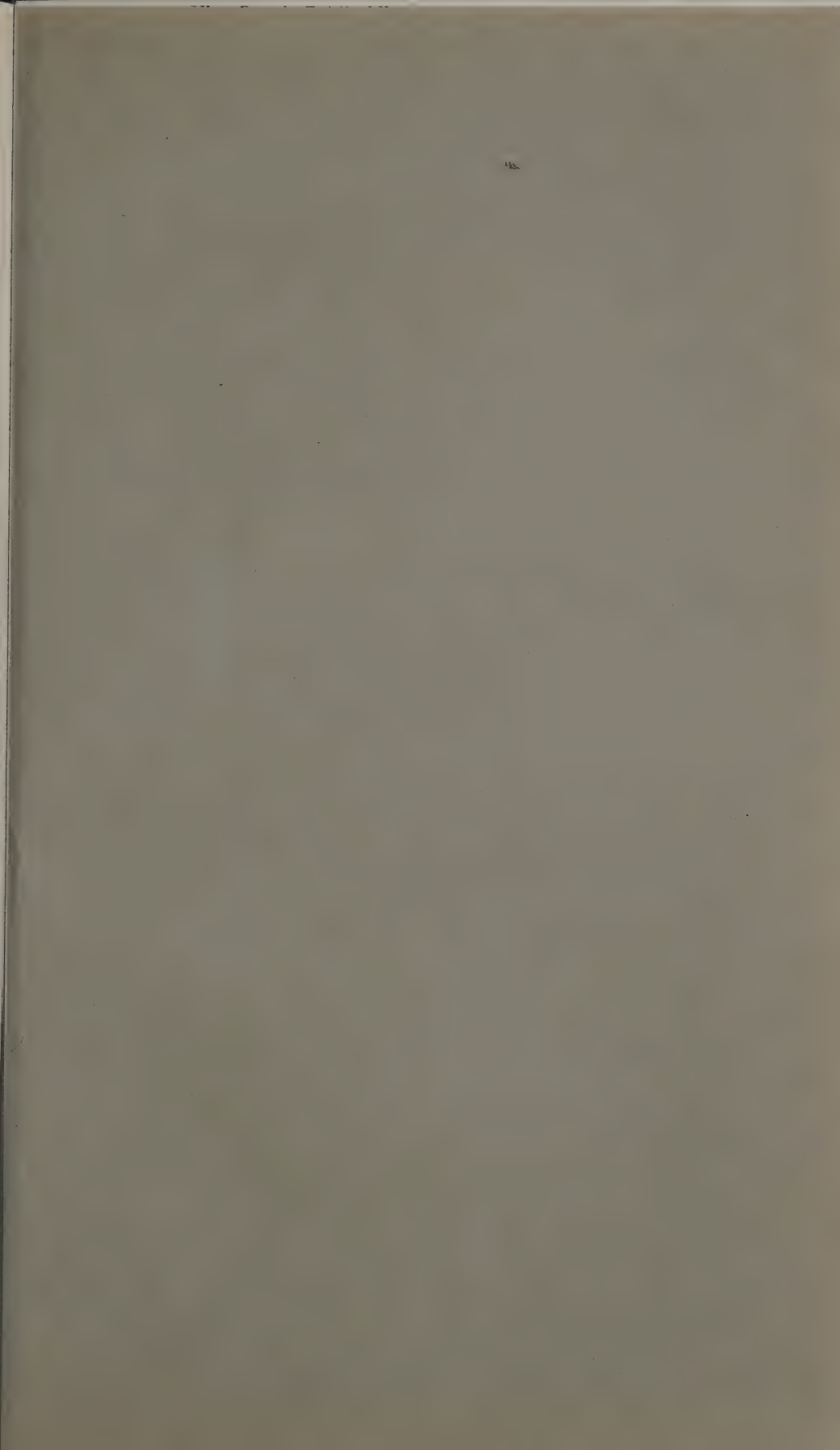


PLATE XXI. B.—Thin cross section of Cannelton cannel coal. This is a spore-cannel coal, composed approximately of 90-95% spore matter. The white lineal spots represent spore matter. At a higher magnification the ground mass between the spores is also shown to be largely composed of spore matter. X100. (After Thiessen and Voorhees.)







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